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Direct CFD Predictions of Low Frequency Sounds Generated by Helicopter Main Rotors

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Motivations

Computational Fluid Dynamics (CFD) methods have demonstrated ample fidelity and precision in simulating the aeromechanics characteristics of helicopter rotors. Many on-going efforts[1-4] have shown that, when coupled to Comprehensive Structural Dynamics (CSD) codes, the combined state-of-the-art CSD/CFD approach is capable of simulating realistic rotor trim solutions, performance, blade structural loads and blade airloads. Much of this success is attributed to CFD's abilities in capturing volumetric flow details surrounding the rotor, such as effects due to the rotor wake, and those due to three-dimensional, unsteady transonic flows over blade surfaces.

In recent years, these CSD/CFD prediction codes have shown even greater improvements with the advent of faster and more powerful computing platforms. Better correlations of predictions to experiment are foremost attributed to an increase in number of grid points used in the computational domain - to the extent that complex rotor aerodynamics and flow details at smaller length scales of interests can now be resolved. In conjunction with efforts tasked to develop new, higher-order finite difference schemes that minimize numerical errors, these coupled-CSD/CFD approaches are promising to be a powerful and useful tool for accurate numerical studies and, eventually, for designing future rotorcraft.

The success in predicting near body aerodynamics of helicopter rotors naturally leads to inquiries if realistic flow-field velocities further away from the rotor (in the far-field and associated with acoustics wave radiation) can be captured by CFD as well. For most applications, the general consensus[5,6] regards direct CFD numerical simulation of external acoustics radiation to be unlikely due to the large spectral bandwidth inherent in the problem and also due to the large disparity in acoustic wave perturbations compared to the mean flow. In terms of CFD implementations, this imposes a constraint that stipulates grid spacing must be sufficiently small to represent the smallest wavelength (i.e. highest frequency) pressure perturbations associated with the rotor noise radiation mechanism. Naturally, smaller grid spacing and large domains of interest (related to observer location) result in larger number of grid points that render direct CFD methods to be impractical in terms of execution time and also may incur additional issues related to numerically instabilities. Numerical dissipation and dispersion errors also impact the ability of CFD schemes to accurately capture the pressure wave propagation.

While these demanding grid spacing and accuracy criteria may limit the use of Direct CFD methods for most acoustics problems, it is deemed less of an issue for military detection noise considerations that focus on the low frequency noise regime[7]. Given the state-of-the-art CFD methods that utilize computational domains, typically on the order 50 million grid points, the likelihood of CFD directly capturing these low frequency noise are quite high, provided that the microphone position is relatively close to the rotor.

If demonstrated, this Direct CFD method will be able to directly predict rotor harmonic noise, without the need of additional post-processing acoustics solvers. Current acoustic solvers in-use are typically based on "hybrid" implementations of Lighthill's acoustic analogy[8] or Kirchhoff surfaces[9] that extend CFD-calculated surface pressures and/or volume velocities around the airfoil to the far-field. While this conventional "hybrid" approach allows for acoustic evaluation further away from the rotor, it also adds an additional layer of computational complexity that requires CFD-generated information to be adapted for input to these acoustics solvers. Hybrid implementations may also suffer from correlations and non-linear effects which can be directly computed from first principles in CFD.

Preliminary Results

This proposed paper will highlight the application of a CSD/CFD methodology[10] currently in-use by the US Army Aerfolightdynamics Directorate (AFDD) to assess the feasibility and fidelity of directly predicting low frequency sounds of helicopter rotors.

The paper will make use of the MD-902 main rotor as the platform for evaluation. Results from both a MD-902/Eglin AFB acoustics flight test performed in 2007[11] and a joint DARPA/Boeing/NASA/Army wind-tunnel test of the Boeing-SMART rotor in 2008[12] (Figures 1 and 2) will be used to assess this new acoustics prediction approach. Acoustics data from these experiments will be compared to CFD calculations from OVERFLOW 2.0 coupled to the comprehensive rotor code CAMRAD-II. As shown in Figure 3, the OVERFLOW code uses structured, overset grids with a near- and off-body discretization paradigm to obtain time-accurate simulations. The high fidelity modeling includes the rotor, pitchcase, hub and PCM fairing. Comparisons to results obtained from conventional acoustics solvers, such as PSU-WOPWOP, will also be presented whenever possible.

Figure 4 illustrates the predicted acoustic time histories obtained from the Direct CFD method for the MD-902 rotor at a level flight condition corresponding to 123-kt airspeed and at a Thrust-to-Solidity ratio of 0.080. Results are shown for a location on the CFD grid (Figure 3) corresponding to a forward, in-plane microphone M13 in the Boeing-SMART wind tunnel test (Figure 2). At this microphone position, noise measurements are dominated by large negative pressure pulses - with strong acoustic amplitudes at lower frequencies that are known to originate from classical thickness and in-plane force mechanisms[13]. Comparisons with noise measurement from the wind tunnel and from flight test (extrapolated) suggest that these dominating features can be consistently captured by the Direct CFD method. However, preliminary results also indicated that the current grid configuration (B.0), with 66.5 millions points, is not capable of simulating the higher frequency contents beyond the fifth blade-passing harmonic. As shown in Figure 4, this frequency-limiting constraint is not an issue for solutions obtained from the conventional "hybrid" method.

Proposed Scope-of-Research Paper

The first part of the paper will be dedicated to point validation of the Direct CFD method for the 123-kt airspeed case shown in Figure 3. Efforts are underway to explore higher-order adaptive grid-generation[14] strategy to increase grid resolution capability at selective portions of the free-field space to enhance capturing of acoustics perturbations associated with higher frequencies. Guidelines for proper grid configuration will be reported.

In addition to point validations and grid studies, results in the paper will also highlight the capabilities of this Direct CFD method in predicting the acoustics radiation over a speed sweep (level flight). Effectiveness of this Direct CFD method on providing relevant acoustic information for detection distance evaluations will also be discussed and presented.

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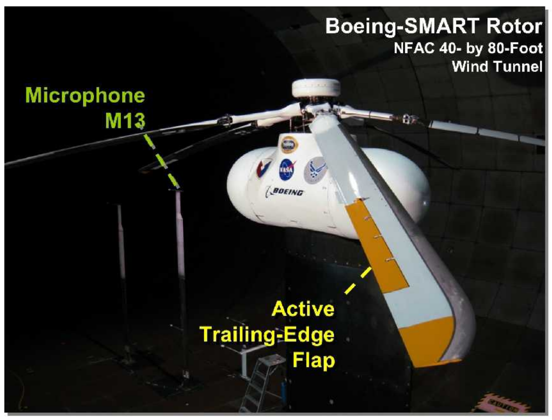

Figure 1. Boeing-SMART Rotor in the NFAC 40- by 80-Foot Wind Tunnel

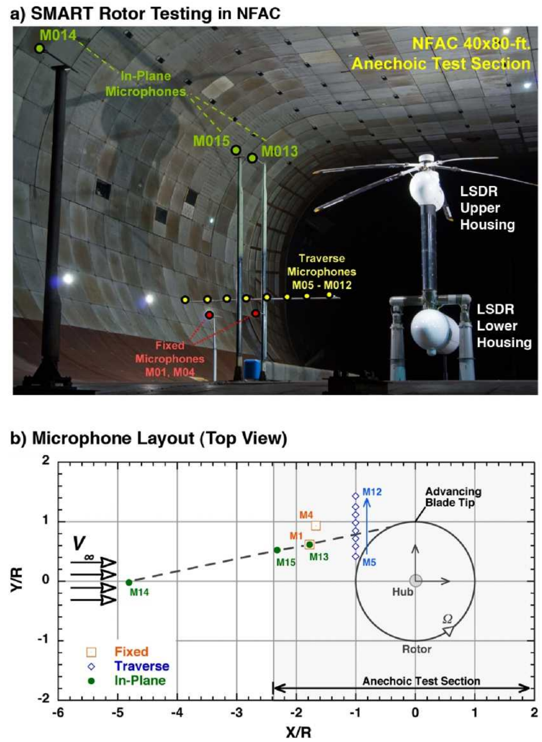

Figure 2. Microphone positions installed for Boeing-SMART Rotor

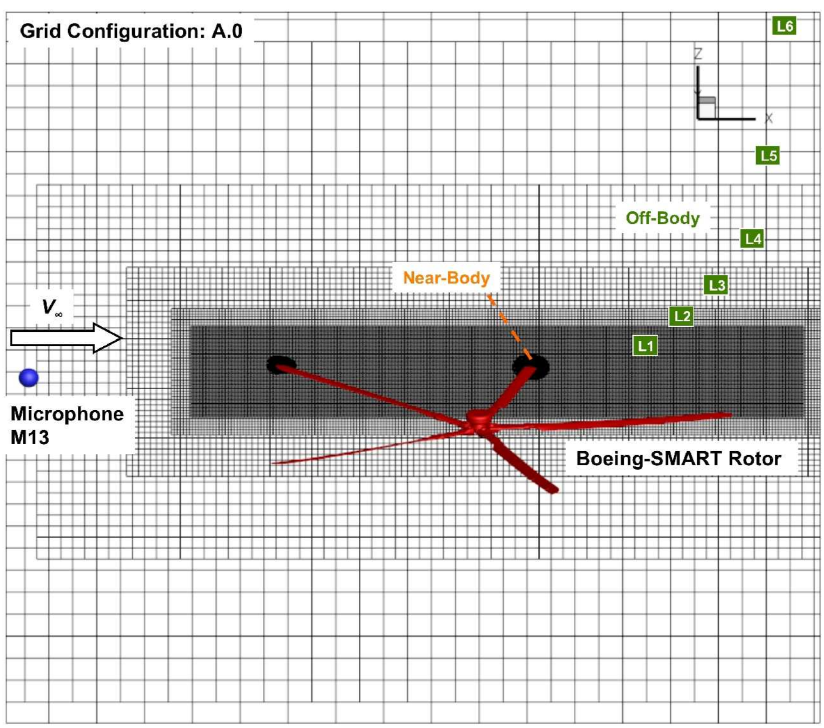

Figure 3. Example of "coarse" grid configuration (A.0) used in current study with 17.0 million grid points.

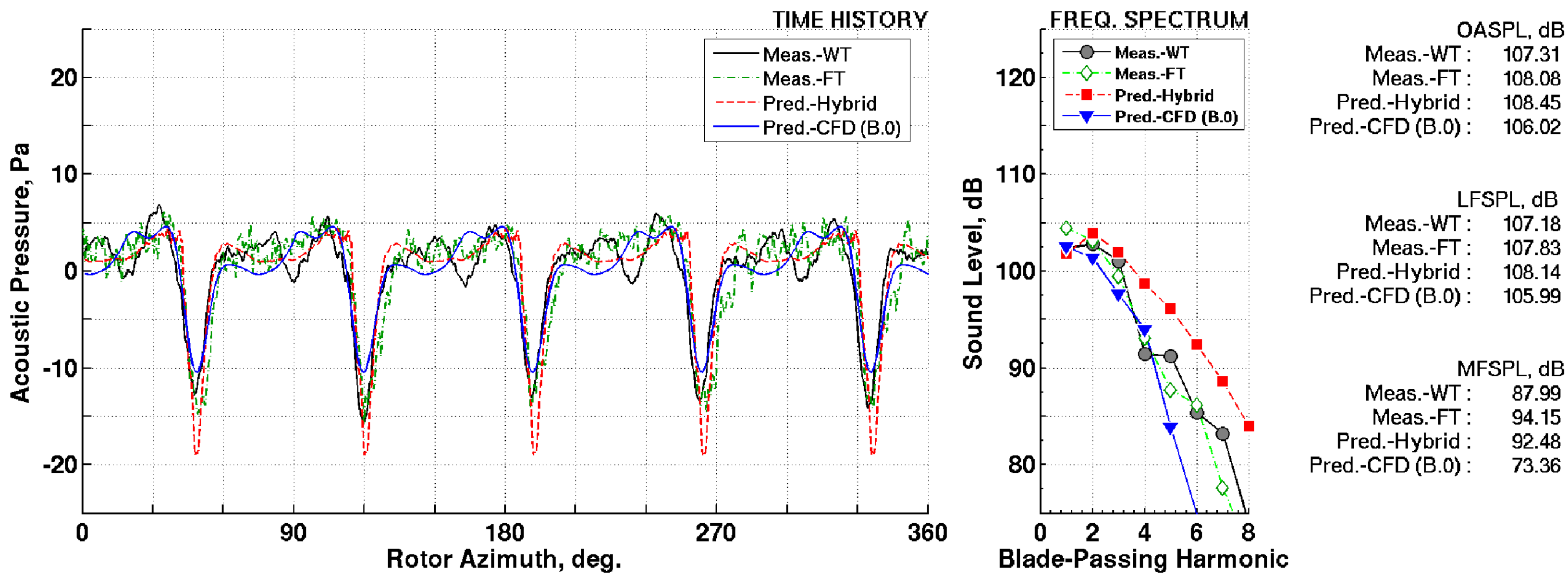

Figure 4. Comparisons of measured and predicted acoustic time histories for MD-902 rotor at 123-kt level flight CFD predictions were obtained with a "fine" grid configuration (B.0) with 66.5 million grid points..